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DESIGNING WITH METAL MATRIX COMPOSITES: WHEN, WHERE AND HOW!

By

Jacques E. Schoutens

Presented at

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ABOUT THE AUTHOR

Mr. Schoutens is Manager of Data Analysis and Special Tasks for the MMCIAC. A physicist, he has been active in various MMC technology assessment studies, data evaluation, and theoretical research in testing methods, test design, and material behavior. While with the General Electric Company, he managed a laboratory for the study of very-high-pressure phenomena. Prior assignments with G.E. included theoretical research in nuclear weapon effects. He also served as engineering manager at Astro Industries in charge of R&D in very-high-temperature, high-pressure research furnaces, hot presses, and laboratory equipment for materials research. At McDonnell Douglas Astronautics, he worked for 9 years as a theoretician in nuclear rocket propulsion and long range unmanned planetary probe studies. His early training was in product design and development, preceded by a period of extensive training as a precision machinist. He is a member of the American Physical Society and the American Association of Physics Teachers. He was a member of General Electric Aerospace Business Group's Advisory Panel on Emerging Technologies. He is a referee for the Journal of Applied Physics and is a contributor on MMC materials to the forthcoming Encyclopedia of Composite Materials to be published by Technomic Publishing Company in 1986. He has published over 60 technical papers and reports covering a wide range of scientific subjects and one book on MMC materials.

DESIGNING WITH METAL MATRIX COMPOSITES:

WHEN, WHERE, AND HOW!

Jacques E. Schoutens
Manager, Data Analysis and Special Tasks
MMCIAC
Kaman Tempo
816 State Street
Santa Barbara, CA 93101

ABSTRACT

This paper presents a design methodology based upon the concepts of structural indices for the selection of metal matrix composite (MMC) materials as substitutes for conventional materials in cases where direct and indirect weight savings, decreased life cycle costs, thermal deformation, wear resistance, and other parameters are important, and for cases where the available space is severely restricted (high loading stress density), thereby requiring high strength and/or high stiffness materials. General design considerations of technical criteria and of operational and cost criteria are briefly discussed. A brief discussion follows of the relevant MMC material property equations used in this paper. These equations are set in the form of parametric functions of two variables: the ratio of fiber-to-matrix elastic moduli and fiber volume fraction. These functions allow for simple graphing or tabulation of composite properties for a wide range of composite materials. The structural indices are then derived to calculate ratios between MMC and conventional material to compare weight to strength, impact resistance, efficiency of columns and plates, flexural rigidity, structural efficiency indices for plates and shells, and the work of fracture.

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INTRODUCTION

Metal matrix composite (MMC) materials have distinct and, in some cases, overwhelming advantages in space and in aircraft applications, but their properties are harder to justify in more conventional and earthbound applications. This technology is still relatively immature compared to reinforced resin composites so that many problems of utilization with conventional materials remain to be solved. Economically, these advanced materials are very expensive compared to unreinforced steel and aluminum, as can be seen in Table 1. The relative values shown in this table indicate that MMC materials do not appear to be competitive with unreinforced steel or aluminum. Note also that in terms of energy required for their fabrication, the trend follows approximately that of cost. The downward trend in cost projected by manufacturers and users alike based on rising production has not materialized. This trend is slower than was anticipated some years ago. However, it is difficult to foresee how costs can reach the low prices of unreinforced metals, even when the latter increase with inflation. A word of caution: cost comparison of raw materials does not really make sense. The cost of the function performed for a given component or subsystem must be considered. Such a value analysis is quite complicated and must factor in the service life of the system, as well as many other considerations [1].

In some areas, MMC offer superior performance; for example, in high-temperature applications such as diesel engine pistons and connecting rods. In designs where weight, stress density, decreased life cycle cost, wear resistance, and thermal stability are overwhelming considerations, MMC materials are finding numerous applications. Part of the impedance to broadening the applications of MMC materials is the relative immaturity and insufficiency of reliable design data, particularly for safety critical applications. As a result, the decision to utilize MMC materials must be based, not only on cost considerations alone, but also on technical and operational grounds. Therefore, this paper presents a design methodology based on the concepts of structural indices to help designers make such decisions and assist in their choice of materials. As the title of this paper suggests, the usefulness of MMC materials must be determined by considering the circumstances (when); the system, subsystem, or component applications (where); and the methodology (how) [2].

ARMY REQUIREMENTS

Army requirements for advanced composite materials, adapted from a presentation by Levitt [3], are summarized here. "The Army has a growing need for new and improved materials to meet increasingly stringent operating requirements in its aircraft, missiles, armament, bridging, tanks, and automotive vehicles" [3]. MMC materials of current interest to the Army are shown in Table 2. In the areas of interest to the Army, the technical goal is to cost-effectively improve performance by replacing existing components with lighter, stronger, stiffer, tougher, and more wear- and heat-resistant components. Table 3 summarizes the technical basis for MMC materials, and Table 4 summarizes current efforts in applying MMC to Army systems.

The original objective of the helicopter drive system was to develop an MMC forward main transmission case for the CH-47D helicopter to reduce noise, vibration, and maintenance requirements. This achievement would greatly increase transmission component life and reduce aircraft maintenance and downtime and life cycle costs. Graphite fiber reinforced magnesium (Gr/Mg) castings are very attractive for transmission cases because of their low density, high stiffness and strength, and excellent machinability.

The Army is also interested in MMC materials applications to various components and airframe structures of the Heavy Lift Helicopter (HLH).

Because of the potential benefits of MMC to Army helicopter landing skid gear components, Bell Helicopter Textron (under an Army contract) has recently evaluated the usefulness of particulate and whisker reinforced silicon carbide for this application. Significant weight savings and improved wear resistance were noted.

The Quick Erectable Antenna Mast (QEAM) consists of a series of telescoping, portable, ground-based antennas being developed for Army use. The structure will consist of particulate or whisker reinforced aluminum, thus improving stiffness and reducing field weight.

Earlier work on applying Gr/Mg to the airborne Battlefield Data System (BDS) antenna indicated that it is the best material for this application because of its very high specific stiffness and strength, near zero thermal expansion coefficient, and good electrical conductivity. Because the thermal deformation resistance of Gr/Mg is the highest of any available material, it has the potential for improving performance by minimizing antenna distortion due to thermal gradients. The Joint Standoff Target Acquisition Radar System (JSTARS) antenna is a follow-on modification of the BDS.

A joint Army/Air Force program to develop manufacturing methods and technology for MMC shafts has been underway. The goal of this program is to reduce the mechanical complexity of the power turbine shaft for an advanced technology engine with the associated benefits of increased unsupported shaft length, fewer support bearings, reduced weight, and improved reliability.

The Army is also pursuing the development of MMC bridging to effect benefits in reduced weight; longer span; increased stiffness, load capacity, and reliability; and improved mobility and joint compatibility. The candidate MMC for bridging include Gr/Al, FP/Al, SiC_p/Al, SiC_w/Al, and continuous SiC filament reinforced Al. Selected bridging structures being studied include the bottom chord, king post, compression chord, and shear web for tactical bridges.

Continuous and discontinuous fiber reinforced aluminum are being investigated for advanced interceptors, and boron carbide particulate reinforced magnesium (B_4C/Mg) is a very attractive replacement for aluminum sabots in the XM829 120-mm armor penetrating munitions.

Particulate and whisker reinforced in 6061-T6 aluminum have been used to improve wear resistance and reduce weight of tank tracks.

Large 120-mm gun tubes require a hard chromium plating which is applied to the interior of the gun tube surface with a large cylindrical copper anode (about 22 feet long by 3 inches in diameter). The anode must be maintained concentric to the gun bore to provide uniform plating thickness. The copper anode is a problem because it is very heavy and deforms easily. MMC are being investigated as a promising lighter and stiffer substitute. The fiber reinforced aluminum composite would be encased in a thin-wall copper tube.

GENERAL DESIGN CONSIDERATIONS

When considering the use of MMC materials in structural applications, it is not meaningful to consider each new structural concept for MMC applications through every stage of analytical details and reiteration of analysis. Such an approach is extremely tedious and may hide the implications of changes in strength, stiffness, density, etc. upon the structures performance. Moreover, it would lead to the development of methodologies which become structure design dependent.

The purpose of this paper is to develop a general methodology that is simple to use and adaptable to any structure. In considering structures in this manner, it is necessary to first consider the operational and cost criteria and the technical criteria that affect the design process. These criteria are shown in Table 5. These are not listed in order of importance. There are interrelationships among operational and cost criteria and technical criteria. For example, the need for high strength may become a determining factor in some structural element or component which overrides cost. On the other hand, the problems of routine inspection may preclude access to some areas of the structure. This would necessitate critical crack lengths that are rather large for ease of visual inspection, which implies a high work of fracture which today is not necessarily obtainable with MMC materials. However, the increasing use of nondestructive inspection methods may soon eliminate the need for visual inspection. The fracture toughness aspect of MMC material properties is not well developed yet, which means that high risks in cost and safety would be involved in ignoring work of fracture where it is critical. These trade-offs must be considered and evaluated during concept evaluation and design analysis. A technical criterion called stress density is shown in the right-hand column of Table 5. Stress density is defined as follows: quite often, structural designs require forces to be transmitted from one component through another, or through a joint or attachment that must occupy a small volume arising from equipment and structural constraints. Thus, a high stress density is the applied force divided by the material cross section of the force transmitter in a small volume. Obviously, it may not be feasible to increase the material thickness of the force transmitter because of such volume constraints. Therefore, to meet design requirements, high strength materials must be employed to meet the required stress density. High stress density implies small spatial volume and, hence, the need for high strength, high stiffness materials. Since stress density is a design variable, there is no general way to define it as a material property.

The general design considerations consist in analyzing qualitatively elements and substructures or components of a design to uncover potential technical and operational weaknesses resulting from the use of conventional materials, and deciding upon these findings whether or not these potential deficiencies can be overcome by the use of MMC materials.

A structure can be conceptually disassembled into elements where high stresses, wear, and other critical factors are seen to emerge. These elements are usually associated with the actual structural elements: a corner in which several struts are joined may be the seat of high stress concentrations and high stress density which, if corrosion sets in, for example, would eventually weaken these joints and cause failure. Members loaded in compression need to be examined to determine the loading stresses relative to the critical buckling load and whether or not the loads are cyclic. The same applies to torsional effects. In this case, dynamic buckling analysis may be required and, if the structural members under consideration are impulse loaded, conventional static buckling analyses are not adequate since most materials exhibit stress-strain behavior dependent on strain rate. In isolating regions of structures, to determine their design adequacies, a number of questions, as shown in Table 6, should be answered. These are by no means all possible questions arising during structural design.

The purpose of the enumeration given in Table 6 is to focus attention on the volume of the element or component under consideration, and to reveal any requirements for thermal or other treatments or the need for materials different from conventional materials. Advanced composites may also be used to advantage with hybrid composites in which some components are cellular solids [4,5].

From the above discussion, it can be seen that all loads on a structure can be reduced to those shown in Table 7. Also shown are the failure states.

The process of analysis discussed in this section is summarized in Figure 1, which shows that the cycle begins with the definition of operational and cost requirements leading to structural performance requirements. This, in turn, leads to structural design and, through various iteration cycles between analysis and material modifications, to an acceptable structure. This is the usual course of development in design. Thus, structural analysis indicates load magnitudes for which conventional materials are ill-suited so that new materials are indicated.

RELEVENT COMPOSITE MATERIAL EQUATIONS

In this section, we summarize currently used equations for the calculation of MMC material properties. The longitudinal elastic modulus is given to a good approximation by

$$E_L = E_f V_f + (1 - V_f) E_m \tag{1}$$

where E_f and E_m are the fiber and matrix elastic moduli, respectively, and V_f is the fiber volume fraction. The transverse elastic modulus is given approximately by

$$\frac{1}{E_T} = \frac{V_f}{E_f} + \frac{(1 - V_f)}{E_m} \quad . \tag{2}$$

Equations 1 and 2 can be written in terms of a constant K_o relating the fiber to the matrix elastic modulus or

$$E_f = K_o E_m \tag{3}$$

so that Equations 1 and 2 become

$$E_L = \{(K_o - 1)V_f + 1\} E_m \tag{4}$$

$$E_T = \left\{\frac{1}{1 - (1 - 1/K_o)V_f}\right\} E_m \quad . \tag{5}$$

These expressions are useful for parametric analysis since, for a given MMC system, K_o is a constant.

The composite strength along the fiber direction is given by

$$\sigma_L = \sigma_{fu}\left\{\left(\frac{K_o - 1}{K_o} - \frac{S_c}{2S}\right) V_f + \frac{1}{K_o}\right\} \quad , \quad S \geq S_c \tag{6}$$

where σ_{fu} is the ultimate tensile strength of the fiber, and S and S_c are the fiber length-to-diameter aspect ratio and critical aspect ratio, defined by

$$S = \frac{L}{2d} \tag{7}$$

and

$$S_c = \frac{\sigma_{fu}}{2\tau_i} \tag{8}$$

where L is the fiber length and d is its diameter. Here, τ_i is the interfacial shear stress between fiber and matrix, a quantity which must be determined experimentally. For E-glass/epoxy, τ_i = 6 MPa (41,370 psi) while for MMCs, $\tau_i \approx \sigma_{my}/2$, where σ_{my} is the matrix yield strength. For short fiber reinforced composites, $S < S_c$, one can either look up the experimental values of composite yield strength from tabulated data or it can be calculated from the following expression

$$\sigma_L = V_f S \tau_i + (1 - V_f)\sigma_{my} \quad , \quad S < S_c \tag{9}$$

where it has been assumed that $E_m \epsilon_1 = \sigma_{my}$, where ϵ_1 is the composite yield strain.

Note that as the fiber becomes very long relative to S_c, that is $S \to \infty$, $S_c/2S \to 0$ and Equation 6 becomes

$$\sigma_L = \frac{\sigma_{fu}}{K_o}\left\{(K_o - 1)V_f + 1\right\} \quad , \quad S \to \infty \tag{10}$$

which has the same form as Equation 4.

Unidirectional fiber reinforced composites are weak when stressed in a direction normal to the fibers. This follows from the fact that fibers usually contribute no transverse strength and the fiber-matrix interface is usually weak [6,7]. Letting σ_i define the interfacial tensile strength, imperfectly bonded composites have a transverse strength determined by

$$\sigma_T = V_f\sigma_i + (1 - V_f)\sigma_m \quad . \tag{11}$$

However, $\sigma_i \neq 2\tau_i$. When the interface is very strong so that $\sigma_i > \sigma_{mu}$, where σ_{mu} is the ultimate matrix tensile strength, then

$$\sigma_T \approx \sigma_{mu} \quad . \tag{12}$$

Equation 12 represents an upper bound. The upper bound is generally difficult to achieve because of the stress concentration created by the fiber [7]. In the case of fibers that can easily be split lengthwise during the application of a transverse stress (which is sometimes the case for boron fibers) where the transverse fiber strength is σ_{fT}, less than σ_i or σ_{mu}, then

$$\sigma_T = V_f\sigma_{fT} + (1 - V_f)\sigma_{mu} \quad . \tag{13}$$

Equation 13 represents a lower bound on the transverse strength of unidirectional fiber reinforced composites. Because transverse strength is usually low and the transverse modulus is relatively high, the transverse failure strain is low.

The Poisson ratio ν_{LT} is related to ν_{TL} by the usual ratio or [6,7]

$$\begin{aligned}\nu_{LT} &= -\frac{E_L}{E_T}\nu_{TL} \\ &= \left\{(K_o - 1)V_f + 1\right\}\left\{1 - (1 - 1/K_o)V_f\right\}\nu_{TL}\end{aligned} \tag{14}$$

using Equations 4 and 5 so that (see Appendix A)

$$\nu_{TL} = V_f\nu_f + (1 - V_f)\nu_m \approx \frac{1}{3}\left\{1 - \frac{1}{4}V_f\right\} \quad . \tag{15}$$

Finally, thermal expansion of composite material can be of some concern. Useful expressions were developed by Schapery [8]. For the longitudinal coefficient of thermal expansion, it is

$$\alpha_L = \frac{\alpha_f V_f K_o + \alpha_m(1 - V_f)}{(K_o - 1)V_f + 1} \tag{16}$$

using Equation 3, and the transverse coefficient of thermal expansion is [9]

$$\alpha_T = \alpha_{Tf} V_f + (1 - V_f)\alpha_{Tm} + \frac{V_f(1 - V_f)(\nu_f E_m - \nu_m E_f)}{V_f E_f + (1 - V_f)E_m} (\alpha_{Lf} - \alpha_{Lm}) \tag{17}$$

where the subscripts Tf and Tm stand for transverse fiber and transverse matrix, respectively, and Lf and Lm stand for longitudinal fiber and longitudinal matrix, respectively. For graphite fibers, $\alpha_{Tf} \neq \alpha_{Lf}$ [7,9], but for most other fibers, $\alpha_{Tf} \simeq \alpha_{Lf}$. Moreover, $\alpha_{Tm} = \alpha_{Lm}$. Thus, setting $\alpha_{Tf} = \alpha_{Lf} = \alpha_f$ and $\alpha_{Tm} = \alpha_{Lm} = \alpha_m$, and using Equations 3 an Equation 17 reduces to the parametric form in K_o and V_f

$$\alpha_T = \alpha_f V_f + (1 - V_f)\alpha_m + \frac{V_f(1 - V_f)(\nu_f - \nu_m K_o)}{\{(K_o - 1)V_f + 1\}} (\alpha_f - \alpha_m) \ . \tag{18}$$

In the next section, we will also be using the plate and shell buckling moduli, which are given as

$$E_p = \frac{E}{1 - \nu^2} \tag{19}$$

and

$$E_s = \frac{E}{\sqrt{1 - \nu^2}} \tag{20}$$

for unreinforced or reinforced isotropic material, where ν is Poisson's ratio and E is the elastic modulus. For unidirectional fiber reinforced composite materials, it has been shown elsewhere [10] that these equations can be represented by

$$E_p = \frac{1}{2}\left\{\frac{\sqrt{E_T E_L}}{1 - \sqrt{\nu_{TL}\nu_{LT}}} + 2G_{TL}\right\} \tag{21}$$

for plate buckling modulus, and for the shell buckling modulus, the smaller values of the following equations being used in design analysis

$$E_{S1} = \left\{\frac{2G_{TL}(E_T E_L)^{1/2}}{1 - \sqrt{\nu_{TL}\nu_{LT}}}\right\}^{1/2} \tag{22}$$

or

$$E_{S2} = \left(\frac{E_T E_L}{1 - \nu_{TL}\nu_{LT}} \right)^{1/2} \tag{23}$$

where [7]

$$\frac{1}{G_{TL}} = \frac{V_f}{G_f} + \frac{(1 - V_f)}{G_m} \; . \tag{24}$$

Here, G_f and G_m are the fiber and matrix shear moduli, respectively. These are related to the elastic moduli by

$$G_{f,m} = \frac{E_{f,m}}{2(1 + \nu_{f,m})} \tag{25}$$

where the subscript stands for either fiber or matrix.

DERIVATION OF STRUCTURAL INDICES

One of the most useful tools in the study of optimum structural design is the application of the principles of dimensional similarity. In structural engineering, this is accomplished with the use of structural indices. A structural index can be defined approximately as a measure of the loading intensity. This means a comparison between the magnitude of the load to be carried and the distance over which this load must be transmitted. The structural index is comparable, in structural design, to the coefficients used in aerodynamics, except that it has dimensional form [11]. To render structural indices to dimensionless form, it is only necessary to divide them by a stress, usually the elastic modulus.

One of the great advantages of this approach is that design proportions that are optimum (minimum weight) for a particular structure are also optimum for structures of any size, provided they all have the same structural index.

In determining optimum design on a weight/strength basis, the two major variables are the material and the configuration of the structure. For simple tension, optimum configuration is a straight line, and the proportions of cross sections have no direct effect on the weight. Consequently, the weight/strength factor is determined entirely by material properties. In the case of compression, the optimum configuration is also a straight line, but the size and shape of the cross section, as well as the constraints (for example, fixed ends, lateral support, and so on), play an important role in the buckling strength of the member. In this case, the material properties and configuration are interrelated. Therefore, for any structural index, it is possible to find a combination of material and configuration that will result in the lightest structure. Obviously, the problem of carrying a load in compression is more difficult and more sophisticated than that of carrying the same load in tension. Therefore, for designs for which weight is a consideration, this problem can become quite severe [11].

The use of numerical factors, dimensionless numbers, or structural indices is not new, and such factors have been developed extensively to deal with structural problems in aircraft [11] and spacecraft design. They show the consequence of choosing some parameters in favor of others and the potential effects of these choices upon the structural design. It is recognized that weight reduction, improved fracture toughness, better area weight-to-stiffness or strength ratios, and improved buckling properties can be understood for a broad class of designs. Consequently, various structural indices can be used to test for the effects of changing geometry or material properties to improve the design by lowering critical stresses.

Weight-Strength

If weight is an important consideration in a structural design, then two important numerical factors in choosing among materials are the specific strength, σ/ρ, and the specific stiffness, E/ρ, where σ is the strength, E is the elastic modulus, and ρ is the material density. The units are lbs-in. or N-m. These factors can also be related to a characteristic material thickness, so that we obtain

$$\frac{\underline{\text{weight/unit area}}}{\text{strength}} = \left(\frac{\rho}{\sigma}\right) t \tag{26}$$

and

$$\frac{\underline{\text{weight/unit area}}}{\text{stiffness}} = \left(\frac{\rho}{E}\right) t \tag{27}$$

where these factors have dimensions of length. The characteristic thickness of the material can be applied to shell or plate thickness, or any other critical dimension which is characteristic of supporting a load. The values of σ and E are the material properties and not the stress due to the load. A material with the highest strength or stiffness efficiency would have the lowest factors given by Equations 26 or 27.

Impact Resistance

Another parameter relevant to structure design, particularly where dynamic loads are involved, is the ratio of impact resistance to the dynamic load, or

$$\frac{\underline{\text{impact resistance}}}{\text{energy delivered}} = \frac{I_R}{E_d} \quad . \tag{28}$$

The impact resistance is a material property that is not very well understood for MMC at the present time. Some available impact and fracture toughness data are shown in Tables 8 through 10 and Figure 2. The energy delivered is the integral of the external force over the time of its application or

$$E_d = \int_0^\tau F(t)dt \tag{29}$$

where $F(t)$ is a time varying force. It may be a periodic force, in which case it can be approximated by a sine-wave, or it may be impulsive, in which case it can be approximated by a narrow square pulse, or a step function. It may be an exponential of the form $P(t) = P_o t \exp(-t/t_m)$ in the case of a pressure wave due to an explosive blast [12], where $P_o = P_{max}/t_m e^{-1}$, where P_{max} is the maximum pressure, t is time, and t_m is the pressure rise time to its peak value. For simplification, a blast pressure pulse could be simplified by a triangle of amplitude P_{max} or $F_{max} = AP_{max}$, where A is the surface area subjected to the pulse, and of duration τ. Then, Equation 29 becomes

$$E_d \simeq \frac{1}{2} F_{max}\tau = \frac{1}{2} AP_{max}\tau \qquad (30)$$

and Equation 28 becomes

$$\frac{I_R}{E_d} = \frac{2I_R}{F_{max}t} \quad . \qquad (31)$$

Efficiency of Columns and Plates

Gordon [13] and Shanley [11] have shown that the efficiency of plates and columns in terms of supporting compression loads is given by

$$e_c = C_0 \left(\frac{\sqrt{E}}{\rho}\right)\left(\frac{\sqrt{F}}{L^2}\right) \qquad (32)$$

for a column, and for a plate

$$e_f = C_1 \left(\frac{\sqrt[3]{E}}{\rho}\right)\left(\frac{F^{2/3}}{L^{5/3}}\right) \qquad (33)$$

where C_0 and C_1 are constants, E and ρ are as mentioned above, L is the length of the plate or column along the loading direction, and F is the load. Because Equations 32 and 33 are used for comparing materials, that is, the efficiency of column design no. 1 versus column design no. 2, the constants cancel in the ratios e_{c1}/e_{c2} or e_{f1}/e_{f2}. The elastic modulus for conventional materials or composite materials given in the previous section is to be used when making numerical comparisons.

In Equations 32 and 33, the terms $\sqrt{E}/\rho$ and $\sqrt[3]{E}/\rho$ are called material parameters or material efficiency criteria [13]. The terms $\sqrt{F}/L^2$ and $F^{2/3}/L^{5/3}$ are called structure loading coefficients [13]. The parameters account for the weakening in compression loaded members due to the Euler effect due to buckling. The critical stress for buckling is always less than the material compressive yield stress because buckling is a geometric effect. These are useful indicator numbers because they point to the direction where improvements are most easily made: either geometrical or material.

The structure loading coefficients indicate that weight savings are achieved with the highest value of these coefficients, that is, by using the most compact and highly loaded devices, cases where MMCs have distinct advantages over conventional materials. However, not much can be done to raise the structure loading coefficients themselves because of fundamental limitations. The effects of low structure loading coefficients can be offset to some extent by the material efficiency criteria ($\sqrt{E}/\rho$ for a column or $\sqrt[3]{E}/\rho$ for a plate), by using material with high specific stiffness values such as composites. Some values for conventional and MMC materials are shown in Table 11. The values in this table show that wood has the highest specific properties even though it has a low value of elastic modulus and density. But for the high stiffness materials, graphite/aluminum composite shows the highest values of the composites.

A simple example can be used to compare, say, steel with graphite/aluminum. For graphite/aluminum, E_c = 390 GPa with V_f = 0.5, and E = 212 GPa for steel (Table 11). The densities of aluminum and steel are 2.7 and 7.8 gm/cm^3, respectively. Then, comparing Gr/Al and steel for a column and a plate, using Equations 32 and 33 gives

$$\frac{(\sqrt{E}/\rho)_{Gr/Al}}{(\sqrt{E}/\rho)_{steel}} = \frac{\sqrt{390}/2.7}{\sqrt{212}/7.8} = 1.36(2.89) = 3.92 \qquad \text{(column)}$$

$$\frac{(\sqrt[3]{E}/\rho)_{Gr/Al}}{(\sqrt[3]{E}/\rho)_{steel}} = \frac{\sqrt[3]{390}/2.7}{\sqrt[3]{212}/7.8} = 1.23(2.89) = 3.54 \qquad \text{(plate)} \quad .$$

It can be seen from these results that an increase in stiffness by a factor of 1.84 (E_c/E) results in an improved stiffness by a factor of 1.36 for a column and 1.23 for a plate. A decrease in the density alone nearly triples (2.89) the plate and column efficiency. Thus, net improvements in efficiency of 3.5 for a plate and 4 for a column are possible by simply changing materials to improve a design. A similar calculation comparing unreinforced aluminum to steel results in a net improvement of only 1.7 for a plate and 2 for a column, the dominant contribution being from density reduction alone, which offsets the negative effects of the lower stiffness of aluminum.

Flexural Rigidity

In the simple bending of beams, the elastic deformation results in a curvature of radius R. If the bending forces result in a moment M, then MR = EI, where EI is the flexural rigidity with I the moment of inertia about the neutral axis. A beam with great stiffness has a high value of EI and, since for a beam of height h and unit width, $I = h^3/12$, so that $EI = Eh^3/12$. The weight of the beam per unit length and width is ρh. Then comparing two materials, a composite with a conventional material (designated by the subscripts c and o) for the same flexural rigidity, they will have their thickness related by

$$E_o h_o^3 = E_c h_c^3 \qquad (34)$$

and the ratio of their weight is $W_o/W_c = \rho_o h_o/\rho_c h_c$, and using Equation 37 gives

$$\frac{W_o}{W_c} = \left(\frac{\sqrt[3]{E_c}}{\rho_c}\right)\left(\frac{\rho_o}{\sqrt[3]{E_o}}\right) . \tag{35}$$

Values given in Table 11 show the advantage of using composite materials when bending stiffness should be maintained at the lowest weight penalty.

Efficiency Structural Indices for Plates and Shells

We now discuss plate and shell efficiency structural indices when these structural elements are loaded in axial compression. The derivations are given in Appendix B. A simple analysis shows that the weight index W/b or W/R versus the load index N_x/b or N_x/R for plates and shells, respectively, exhibits a knee as shown in Figures 3 and 4 [10]. Here, N_x is the axial compressive load, b is the plate width, R is the shell radius, and W is the weight. In Figures 3 and 4, the right-hand sides of these curves have slopes of 45 degrees representing the region in which the structure is limited by material strength. The left-hand sides of these curves correspond to the elastic stability limited region, that is, the region limited by plate or shell buckling. The knee is a discontinuity corresponding to the point at which failure is (hypothetically) simultaneously a material and a stability failure [10]. For shells under lateral pressure and under combined load, the corresponding slopes of the elastic stability region of the curve vary between those for shells and plates under axial load decreasing from $E_s^{1/2}$ for shells under axial load to $E_s^{1/2.75}$ for shells under axial compression and lateral pressure [10]. This result is approximate because the length of the shell must also be considered. It can be shown (see Appendix B) that below the knee

$$\frac{W}{b} = \rho\left(\frac{t}{b}\right) = \rho\sqrt{\frac{N_x/b}{\pi^2 E_p/3}} \qquad \text{(plate)} \tag{36}$$

and

$$\frac{W}{R} = \rho\left(\frac{t}{R}\right) = \rho\sqrt[3]{\frac{N_x/R}{E_s/2\sqrt{3}}} \qquad \text{(shell)} \tag{37}$$

In Equations 36 and 37, E_p is the plate buckling modulus given by Equation 19 for unreinforced materials and Equation 21 for composite materials, and E_s is the shell buckling modulus given by Equation 20 for unreinforced materials and Equation 22 or 23 for composite materials.

In general, the designer has no control over the values of N_x/b or N_x/R to be satisfied. If the design value of the load index is less than that for the knee of the curve, <u>simply increasing the strength of the material will not result in weight reduction</u>. Moreover, if the design value is above the knee, <u>simply increasing the buckling efficiency is of no merit either</u>. Consequently, the knee itself is an important index in efficient design [10]. The efficiency index for a plate in axial compression loading is (see Appendix B)

$$e_p^* = \left\{\left(\frac{\sqrt{E_p}}{\rho}\right)\left(\frac{\sigma_{cu}}{\rho}\right)\right\}^{1/2} \qquad \text{(plate)} \tag{38}$$

and

$$e_s^* = \left\{\frac{E_s \sigma_{cu}}{\rho^3}\right\}^{1/3} \qquad \text{(shell)} \tag{39}$$

where σ_{cu} is the ultimate compressive strength of the material. Equations 38 and 39 can now be used to obtain a loading intensity at which the efficiency indices are attained. For a plate (see Appendix B), it is

$$\left(\frac{N_x}{b}\right)_{e_p^*} = \frac{\sigma_{cu}^{3/2}}{\sqrt{\pi^2 E_p/3}} \tag{40}$$

and for a shell in axial compression, it is

$$\left(\frac{N_x}{R}\right)_{e_s^*} = 2\sqrt{3}\left(\frac{\sigma_{cu}^2}{E_s}\right) . \tag{41}$$

In the above analysis, the composite density can be obtained from the rule of mixture, identical to Equation 1, where ρ_c, ρ_f, and ρ_m are substituted for E_L, E_f, and E_m, respectively.

Work of Fracture

The work of fracture between two different materials can also be related to the stress intensity parameter, K_{IC}, which is a measure of the frangibility of the material. However, K_{IC} also depends on the methods used to obtain this parameter and on the loads. A simple relationship between K_{IC}, the elastic modulus, and the work of fracture, W_F, is

$$W_F = C\,\frac{K_{IC}^2}{E} \tag{42}$$

where C is a constant. In comparing two materials, the ratio W_{F1}/W_{F2}, the constant is eliminated and, thus, not relevant here. Equation 42 can be used to compare unreinforced metals with metals reinforced with whiskers or particulates. Equation 42 does not apply to continuous fiber reinforced MMCs because the fracture process is complex and quite different from conventional materials. Present fracture theories for continuous fiber reinforced MMCs are inadequate for failure prediction. Maximum fracture toughness values for particulate and whisker SiC (SiC_p, SiC_w) reinforced aluminum are given in Table 10.

Some useful design data are included in Tables 12 through 19.

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APPENDIX A

Equation 15 is [7]

$$\nu_{TL} = V_f \nu_f + (1 - V_f)\nu_m \tag{A1}$$

where ν_f and ν_m are Poisson ratios of the fiber and the matrix material, respectively. For typical fiber materials, ν_f = 0.2 for Al_2O_3, 0.21 for boron, 0.35 for carbon, and 0.19 for SiC, while for typical matrix materials, ν_m = 0.345 (Al), 0.343 (Cu), 0.287 to 0.295 (steel), 0.291 (Mg), 0.34 (epoxy), and 0.33 (polyimide). From these data, the average values of Poisson ratios are $\bar{\nu}_f$ = 0.24 and $\bar{\nu}_m$ = 0.32 so that Equation A1 becomes

$$\nu_{TL} = 0.24\ V_f + 0.32\ (1 - V_f)$$

$$\simeq \frac{1}{3}\left(1 - \frac{V_f}{4}\right) \tag{15}$$

where $\bar{\nu}_f = 0.24 \simeq 1/4$ and $\bar{\nu}_m = 0.32 \simeq 1/3$ are used.

APPENDIX B

In this Appendix, we derive Equations 36 and 37. This derivation follows that of Dow and Derby [10]. The weight of a plate or shell is proportional to the density and inversely proportional to the stress/density ratio. Thus

$$\frac{t}{b} = \frac{N_x/b}{\sigma_{cu}} \quad , \quad \frac{W}{b} = \frac{\rho(N_x/b)}{\sigma_{cu}} \quad \text{(plate)} \tag{B1}$$

$$\frac{t}{R} = \frac{N_x/R}{\sigma_{cu}} \quad , \quad \frac{W}{R} = \frac{\rho(N_x/R)}{\sigma_{cu}} \quad \text{(shell)} \tag{B2}$$

and below the knee (elastic stability region)

$$\frac{N_x}{b} = \sigma_{crp}\left(\frac{t}{b}\right) \quad \text{(plate)} \tag{B3}$$

$$\frac{N_x}{R} = \sigma_{crs}\left(\frac{t}{R}\right) \quad \text{(shell)} \tag{B4}$$

where σ_{crp} and σ_{crs} are the elastic buckling stresses for plates and shells, respectively. These are defined in standard texts on the strength of materials. Consequently, Equations B3 and B4 become above the knee

$$\frac{N_x}{b} = \frac{\pi^2}{3}\left(\frac{t}{b}\right)^3 E_p \quad \text{(plate)} \tag{B5}$$

$$\frac{N_x}{R} = \frac{1}{2\ \ 3}\left(\frac{t}{R}\right)^2 E_s \quad \text{(shell)} \qquad \text{(B6)}$$

and below the knee

$$\frac{t}{b} = \sqrt{\frac{N_x/b}{\pi^2 E_p/3}} \quad \text{(plate)} \qquad \text{(B7)}$$

$$\frac{t}{R} = \sqrt[3]{\frac{N_x/R}{E_s/2\sqrt{3}}} \quad \text{(shell)} \qquad \text{(B8)}$$

so that below the knee,

$$\frac{W}{b} = \rho\left(\frac{t}{b}\right) = \rho\sqrt{\frac{N_x/b}{\pi^2 E_p/3}} \quad \text{(plate)} \qquad \text{(36)}$$

$$\frac{W}{R} = \rho\left(\frac{t}{R}\right) = \rho\sqrt[3]{\frac{N_x/R}{E_s/2\sqrt{3}}} \quad \text{(shell)} \qquad \text{(37)}$$

which are Equations 36 and 37 in the text. Equations 38 and 39 were developed by Dow and Derby [10] by combining Equations B1 and B3 to yield Equation 40 and combining Equations B2 and B4 to yield Equation 41.

Table 1. Approximate relative cost comparison between MMCs and conventional materials.

Material	Relative Cost
Steel plate (hot rolled)	1
Aluminum plates and castings	1 to 4
SiC/Al	600
Boron/Al	1,800
Graphite/Al, graphite/Mg	4,800 to 20,000

Table 2. MMC materials of current interest to the Army.

FP[a]/aluminum
FP/magnesium
Graphite/aluminum
Graphite/magnesium
SiC[b]/aluminum
SiC(cont.)/titanium
Boron carbide/magnesium

[a]Dupont designation for polycrystalline aluminum oxide fiber.

[b]Particulate, whisker, or continuous fiber silicon carbide.

Table 3. Technical basis for MMC applications for the Army. [3]

Exceeds properties of unreinforced materials
Cost effective
Reduced weight
Improved performance
Reduced life cycle costs
"Tailored" properties
Unique properties:
Elevated temperature strength
Laser survivability
Controlled thermal stability
Abrasion and wear resistance
Electrical and thermal conductivity

Table 4. Current efforts in MMC applications to Army systems. [3]

Systems	Specific Components
Aircraft	Stiffened transmission cases: FP/Mg for CH-47D engine nose gear box Dimensionally stable structures: JSTARS antenna Stiffened shafts: advanced technology demonstrator engine
Missiles	BMD advanced interceptor: substructure
Armanent	Sabots: long-rod penetrators Gun tube anodes
Tanks	Track shoes: M-1 tank
Bridging	Bottom chord: heavy assault bridge King post: generic Compression chord: tri-arch bridge

Table 5. Factors to be considered in assessing improvements in structures.

Operational and Cost Criteria	Technical Criteria
Weight	Strength
Indirect weight saving	Stiffness
Cost	Stress density
Maintainability	Critical crack length
Deployability	Work of fracture
Machinability	Corrosion resistance
Repair	Geometrical effects on structural stability
Performance	Weight
Reliability	Wear
Life cycle cost	Repairability
Simplicity	
Inspection	
Safety	

Table 6. Questions which relate to structural design adequacy.

1. Are there regions, holes, bolts, weldments, webs, and so on which are more highly stressed than adjacent regions?
2. How large are the stress concentration factors?
3. Are the applied stresses anywhere likely to be larger than the material strength? (Ordinary metals tend to be strain rate dependent in their strength; that is, an impulse loaded steel has somewhat greater yield strength than for equal static loading.) [12]
4. Are wear and corrosion likely to result in short life? Is this lifetime lower than the required operational lifetime?
5. Are bending moments resulting in flexural rigidity values, EI, greater than the material can withstand? Would increasing E (or I) result in a safe structure? Longer life and smaller volume? Lower weight?
6. Are fatigue and toughness requirements met?
7. Are there serious impulsive loads which are likely to cause brittle fracture?
8. Are safe crack lengths detectable in routine inspection? What is an acceptable crack length?
9. Are the maintenance and repair needed between operation easily and readily performed? Are they costly?
10. Can stressed regions be increased in dimensions rather than solve the problem with high strength high stiffness advanced materials?

Table 7. Basic loads and failure states.

Loads	Failure States
Tension	Fracture
Compression	Buckling
Flexure	Wear
Torsion	Corrosion
Shear	Plastic yielding
Combined loads	

Table 8. Summary of thin-specimen izod impact-strength results and comparisons with some other materials (specimen nominal dimensions: 1.27-cm-wide by 1.52-mm-thick). [14]

Laminate Type	Constituents	Test Direction	Izod Impact Strength (kJ/m)[a]		Number of Specimens
			Low	High	
I	Gr/Ep	Longitudinal	1.45	1.59	4
		Transverse	0.19	0.21	2
II	B/Al[b]	Longitudinal	1.23	1.27	2
		Transverse	1.01	1.10	2
III	B/Al[c]	Longitudinal	0.68	0.96	2
		Transverse	0.43	0.71	4
IV	Ti, B/Al	Longitudinal	1.09	1.13	2
		Transverse	0.79	1.00	4
V	Superhybrid (Ti, B/Al, Gr/Ep)	Longitudinal	2.82	3.20	2
		Transverse	0.82	0.90	2
Other Materials					
HT-S/PMR-PI[d]		Longitudinal	0.91	0.92	2
		Transverse	0.17	0.19	2
Glass-fabric/epoxy			1.11	1.13	3
102-μm-diameter B/6064 Al		Longitudinal	1.13	1.21	2
Aluminum 6061			3.36	4.07	2
Titanium (6Al-4V)			11.23	11.38	2

[a] To convert kJ/m to ft-lbf/in., divide by 53.4×10^{-3} (see ASTM D 256).

[b] Diffusion-bonded.

[c] Adhesive-bonded.

[d] PMR = polymerization of monomeric reactants; PI = polyimide.

Table 9. Toughness values (in kJ m^{-2}) taken from impact tests at 20°C. [7]

System		B/Al Alloy (6061)	W/Ni[a] Alloy	NbC/Ni[a]	(CoCr)/ $(CrCo)_7C_3$ [a]
V_f		0.5	0.6	0.11	0.3
Toughness		6[b]	9[c]	340	94[d]
		1.5[e]	--	--	17[d]
		1.5[e]	--	--	14[d]
	Matrix	130	240	630	--

[a] In situ composites.

[b] Toughness increased with increasing V_f in range 0.3 to 0.5.

[c] Toughness increased to 100 kJ m^{-2} at 370°C, and 500 kJ m^{-2} at 1,000°C. Hot working the material increased the 20°C toughness to 44 kJ m^{-2}.

[d] Slow bending tests gave much lower values (approximately 1/10).

[e] Toughness independent of V_f in the range 0.3 to 0.5.

Table 10. Instrumented impact data. [15]

Material	Heat Treatment	Energy Dissipated: Notched (ft-lbs)	Energy Dissipated: Unnotched (ft-lbs)	K_{max} (ksi $\sqrt{in.}$)
6061	T651	10.0	>150	32.0
7075	T6	4.1	--	47.9
20 v/o SiC_w/2124	0	1.38	8.3	22.1
	T4	0.95	8.0	32.3
25 v/o SiC_p/2124	0	1.80	7.5	23.1
	T4	0.98	8.2	29.0
20 v/o SiC_p/6061	0	4.47	18.8	20.8
	T6	0.80	8.4	22.0

Notes: Full-sized impact test data. All peak aged notched composites absorb less than 1 ft-lb. The 6061 matrix composite in the 0 condition absorbs significantly greater energy than other composites. Comparison of K_c calculated from maximum load indicates SiC_p/6061 has significantly lower fracture toughness than unreinforced 6061.

Table 11. Stiffness-density parameters for a number of materials.

Material	Density, ρ (gm/cm^3)	Longitudinal Elastic Modulus, E (GPa)	E/ρ ($\times 10^5\ cm^2 sec^{-2}$)[a]	$E^{1/3}/\rho$ (plate)	$E^{1/2}/\rho$ (column)
Aluminum	2.70	71	26.3	1.53	3.12
Magnesium	1.74	42	24.1	2.04	3.73
Polyethylene	0.93	0.2	0.22	0.63	0.48
Steel	7.87	212	26.9	0.76	1.85
Titanium	4.51	120	26.6	1.09	2.43
Tungsten	19.3	411	21.3	0.39	1.05
Wood (Sitka spruce)	0.39	13	33.3	6.03	9.25
Zirconium	6.49	94	14.5	0.70	1.49
SiC(whisker)/Al (20 v/o)	2.7	100	37.1	1.72	3.70
Gr/Al (50 v/o)	2.7	390	144.4	2.71	7.31
B/Al (50 v/o)	2.50	230	92.0	2.45	6.07
Borsic/Ti (45 v/o)[b]	3.68	220	59.8	1.64	4.03
Al_2O_3/Al (50 v/o)	3.60	210	58.3	1.65	4.03
SiC(cont.)/Al (50 v/o)	2.93	230	78.5	2.09	5.18
SiC(cont.)/Ti (35 v/o)	3.93	260	66.2	1.62	4.10
Gr/Ni (50 v/o)	5.34	310	58.1	1.27	3.30

[a] Thus, for example, 26.3 is $26.3 \times 10^5\ cm^2 sec^{-2}$.

[b] Borsic is a trade name for boron filament coated with SiC.

Table 12. Typical properties of constituent fiber reinforcements for metal-metal laminates (along the fiber). [14]

Fiber	Density $(g/cm^3)^a$	Melting Point (°C)	Heat Capacity $[kJ/(kg \cdot K)]^b$	Thermal Conductivity $[W/(m \cdot K)]^c$	Coefficient of Thermal Expansion $(10^{-6}/°C)$	Tensile Strength $(MPa)^d$	Modulus $(GPa)^d$	Diameter (μm)	Remarks
Boron on tungsten	2.49	2,100	1.3	38	5.0	3,620	400	102-203	Monofilament
Borsic	2.71	2,100	1.3	38	5.0	3,100	400	102-203	Monofilament
Boron on carbon	2.21	2,100	1.3	38	5.0	3,450	360	102-203	Monofilament
Graphite									
PAN HM	1.86	3,650	0.7	1,003	-1.1	2,210	380	7	10,000 filaments per ton
PAN HTS (T300)	1.74	3,650	0.7	1,003	-1.1	2,340	210	8	3,000 filaments per yarn
Rayon (T50)	1.66	3,650	0.7	1,003	-1.1	2,170	390	6	1,440 filaments per 2-ply yarn
Thornel 75 (T75)	1.83	3,650	0.7	1,003	-1.1	2,660	520	5	1,440 filaments per 2-ply yarn
Pitch (type P)	1.99	3,650	0.7	1,003	-1.1	1,380	340	5-10	2,000 filaments per yarn
Pitch UHM	2.05	3,650	0.7	1,003	-1.1	2,410	690	11	2,000 filaments per yarn
Silicon carbide on tungsten	3.32	2,690	1.2	16	4.3	3,100	430	102-203	Monofilament
Silicon carbide on carbon	3.04	2,690	1.2	16	4.3	3,450	400	102	Monofilament
Beryllium	1.86	1,280	1.9	150	11.5	970	290	127	Monofilament
Alumina (FP)	3.96	2,040			8.3	1,520	380	20	210 filaments per yarn
Glass-S	2.49	840	0.7	13	5.0	4,140	80	9	1,000 filaments per strand
Glass-E	2.49	840	0.7	13	5.0	2,700	70	9	1,000 filaments per strand
Molybdenum	1.02	2,620	0.3	145	4.9	660	320	127	Monofilament
Steel	7.75	1,400	0.5	29	13.3	2,070	210	127	Monofilament
Tantalum	16.88	3,000	0.2	55	6.5	1,520	190	508	Monofilament
Tungsten	19.38	3,400	0.1	168	4.5	3,170	390	381	Monofilament
Whisker ceramic Al_2O_3	3.96	2,040	0.6	24	7.7	42,760	450	10-25	
Metallic (Fe)	7.75	1,540	0.5	29	13.3	13,100	200	127	

[a] To convert g/cm^3 to $lb/in.^3$, divide by 27.68.

[b] To convert $kJ/(kg \cdot K)$ to $Btu/(lb \cdot °F)$, divide by 4.184.

[c] To convert $W/(m \cdot K)$ to $Btu \cdot ft/(ft^2 \cdot h \cdot °F)$, divide by 1.729.

[d] To convert MPa to psi, multiply by 145; to convert GPa to psi, multiply by 145,000.

Table 13. Coefficients of thermal expansion of fibers. [7]

Fiber	α_f (μK^{-1})	Fiber	α_f (μK^{-1})
Alumina	6.2-6.8	Kevlar	59[a]
Asbestos	9.2	Molybdenum	5.0
Beryllium	12	S-glass	8.9
Boron	8.3	Silicon carbide	4.8
Carbon	8.0[a]	Steel	12
E-glass	15.5	Tungsten	4.3

[a]Radial expansion coefficient. Axial coefficients are 0.5 μK^{-1} for carbon and -2 μK^{-1} for Kevlar.

Table 14. Representative values for strength, modulus, and maximum use temperature of inorganic fibers, whiskers, and planar materials (representative values only are given[a]). [7]

Material	Density ($Mg\ m^{-3}$)	Strength (GPa)	Young's Modulus (GPa)	Temperature (°C)
Chrysotile asbestos	2.5	5.5	160	500
Amphibole asbestos	3.3	4.1	190	300
E-glass	2.54	3.4	72	550
S-glass	2.48	4.8	85	650
Fused silica	2.2	5.8	72	750
Boron	2.6	3.5	420	700[b]
Graphite (stiff)	1.9	2.3	377	2,500[b]
Graphite (strong)	1.8	2.8	233	2,000[b]
Al_2O_3 fibers	4.0	2.0	470	800
SiC fibers	3.4	2.3	480	900
Al_2O_3 whiskers	4.0	15	2,250[c]	1,200
SiC whiskers	3.2	21	840[c]	1,600
BeO whiskers	3.0	6.9	720[c]	1,500
SiC platelets	3.2	10	480	1,600
AlB_2 platelets	~2.7	~6	~500	>1,000
Mica platelets	2.8	3.1[d]	226	400

[a]There is considerable variation in values reported for many of these materials. The temperatures are only intended as some indication of relative resistance to heating. In practice, maximum temperatures depend on stress and chemical environment.

[b]500°C in oxidizing atmosphere.

[c]Maximum value, with most favorable crystallographic orientation.

[d]Maximum value, with perfect edges. In practice, strength of small mica flakes ~0.85 GPa.

Table 15. Typical properties of metal matrices and metallic constituents for metal-metal laminates. [14]

Metal	Density (g/cm^3)[a]	Melting Point (^oC)	Heat Capacity [kJ/(kg-K)][b]	Thermal Conductivity [W/(m-K)][c]	Coefficient of Thermal Expansion ($10^{-6}/^oC$)	Tensile Strength (MPa)[d]	Modulus (GPa)[d]	Remarks
Aluminum	2.8	580	0.96	171	23.4	310	70	6061 (T6)
Beryllium	1.9	1,280	1.88	150	11.5	620	290	Annealed
Copper	8.9	1,080	0.38	391	17.6	340	120	Oxygen-free hardened
Lead	11.3	320	0.13	33	28.8	20	10	1-percent Sb
Magnesium	1.7	570	1.00	76	25.2	280	40	AZ31B-H24
Nickel	8.9	1,440	0.46	62	13.3	760	210	Nickel 200 hardened
Niobium	8.6	2,470	0.25	55	6.8	280	100	
Steel	7.8	1,460	0.46	29	13.3	2,070	210	Ultra-high strength (MOD.H-11)
Superalloy	8.3	1,390	0.42	19	16.7	1,100	210	Inconel X-750
Tantalum	16.6	2,990	0.17	55	6.5	410	190	
Tin	7.2	230	0.21	64	23.4	10	40	
Titanium	4.4	1,650	0.59	7	9.5	1,170	110	Ti-6 Al-4 V
Tungsten	19.4	3,410	0.13	168	4.5	1,520	410	
Zinc	6.6	390	0.42	112	27.4	280	70	Alloy agada

[a] To convert g/cm^3 to $lb/in.^3$, divide by 27.68.

[b] To convert kJ/(kg-K) to Btu/(lb-^oF), divide by 4.184.

[c] To convert W/(m-K) to Btu-ft/(ft^2-h-^oF), divide by 1.729.

[d] To convert MPa to psi, multiply by 145; to convert GPa to psi, multiply by 145,000.

Table 16. Typical mechanical properties of metal matrix composites. [14]

Fiber	Matrix	Reinforcement (v/o)	Density $(g/cm^3)^a$	Longitudinal Tensile Strength $(MPa)^b$	Longitudinal Modulus $(GPa)^b$	Transverse Tensile Strength $(MPa)^b$	Transverse Modulus $(GPa)^b$
G T 50	201 Al	30	2.380	620	170	50	30
G T 50	201 Al	49		1,120	160		
G GY 70	201 Al	34	2.380	660	210	30	30
G GY 70	201 Al	30	2.436	550	160	70	40
G HM pitch	6061 Al	41	2.436	620	320		
G HM pitch	AZ31 Mg	38	1.827	510	300		
B on W, 142-μm fiber	6061 Al	50	2.491	1,380	230	140	160
Borsic	Ti	45	3.681	1,270	220	460	190
G T 75	Pb	41	7.474	720	200		
G T 75	Cu	39	6.090	290	240		
FP	201 Al	50	3.598	1,170	210	(140)	140
SiC	6061 Al	50	2.934	1,480	230	(140)	140
SiC	Ti	35	3.931	1,210	260	520	210
SiC whisker	Al	20	2.796	340	100	340	100
B_4C on B	Ti	38	3.737	1,480	230	>340	>140
G T 75	Mg	42	1.799	450	190		
G HM	Pb	35	7.750	500	120		
G T 75	Al-7% Zn	38	2.408	870	190		
G T 75	Zinc	35	5.287	770	120		
G T 50	Nickel	50	5.295	790	240		
G T 75	Nickel	50	5.342	828	310	30	40
G (81.3 μm)	2024 Al	50	2.436	760	140		
G (142 μm)	2024 Al	60	2.436	1,100	180		
Superhybrid	Grafitic	60	2.048	860	120	220	60
Superhybrid	S-glass	60	2.159	740	80	190	30
Superhybrid	Kevlar	60	1.799	700	80	190	10

[a] To convert g/cm^3 to $lb/in.^3$, divide by 27.68.

[b] To convert MPa to psi, multiply by 145; to convert GPa to psi, multiply by 145,000.

Table 17. Maximum temperatures for metals reinforced with boron, carbon, and tungsten fibers. [7]

System	Temperature (°C)	Remarks
C/Al	500	Al contains 12-percent Si
B/Al	540	B coated with SiC
B/Ti	650	B coated with SiC
B/Ti	540	Oxygen present; B coated
C/Ni	800	
C/Ni	600	Oxygen present
W/Ni	1,200	W coated with HfC

Table 18. Poisson's ratios for various fiber and matrix materials. [7]

Metal	ν	Polymer	ν	Ceramic	ν
Aluminum	0.345	Epoxy	0.34	Alumina	0.20
Copper	0.343	Kevlar[a]	0.35	Boron	0.21
Iron (steel)	0.287-0.295	Nylon	0.33	Carbon	0.35[a]
Magnesium	0.291	Polycarbonate	0.37	Cement	0.26
Molybdenum	0.293	Polyester	0.34	Glass	0.22
Nickel	0.293	Polyimide	0.33	Silica	0.17
Tungsten	0.280	Polystyrene	0.33	Silicon	0.27
				Silicon carbide	0.19

[a]Transverse shrinkage of fibers.

Table 19. Approximate values for the hardness and toughness of some materials. [7]

Material	Hardness (Kg/mm^2)	Work of Fracture ($kJ\ m^2$)	Material	(Kg/mm^2)	Work of Fracture ($kJ\ m^2$)
Diamond	8,400	--	High-strength Al alloy	180	10
Alumina	2,600	0.02	Pure aluminum	20	>100
Maraging steel	600	50	Polycarbonate	20	3
Hard tungsten	450	0.02	Epoxy resin	18	0.1
Glass	400	0.005	Wood, across the grain	6	20
Titanium (99%)	200	30	Wood, parallel to the grain	3	0.015

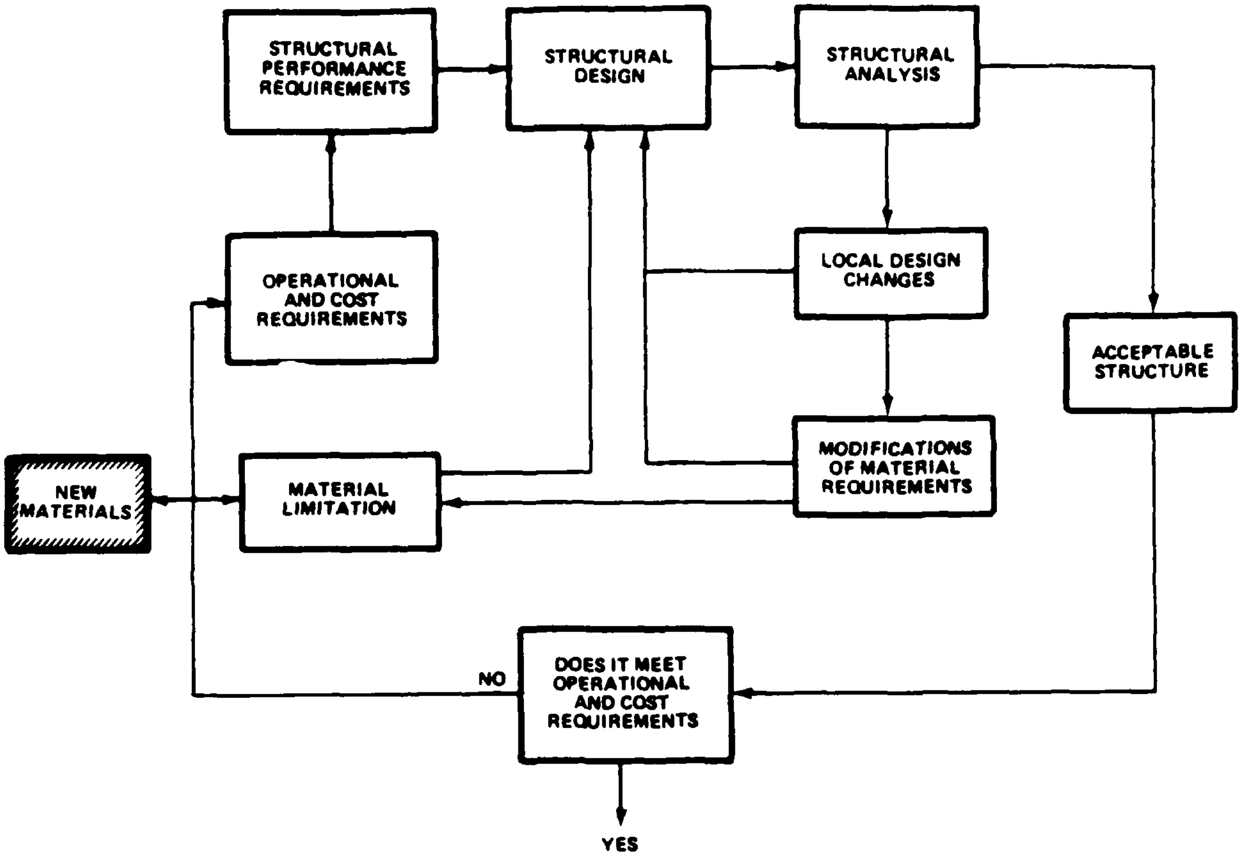

Figure 1. Diagram for material selection procedure.

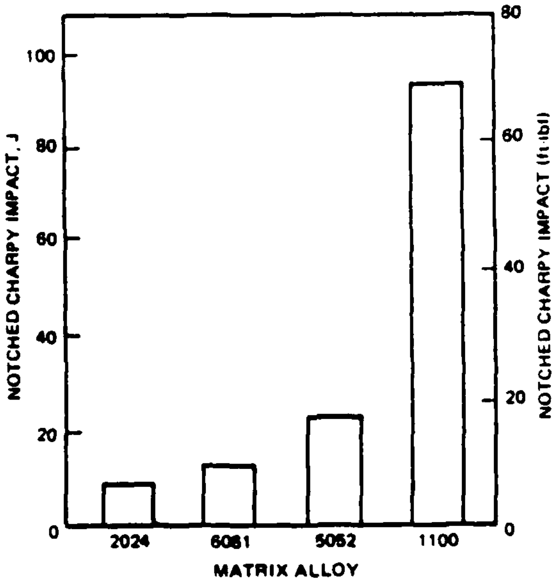

Figure 2. Impact resistance of B/Al unidirectional metallic-matrix laminates (203-μm-diameter fiber, 0.50 fiber-volume ratio). [14]

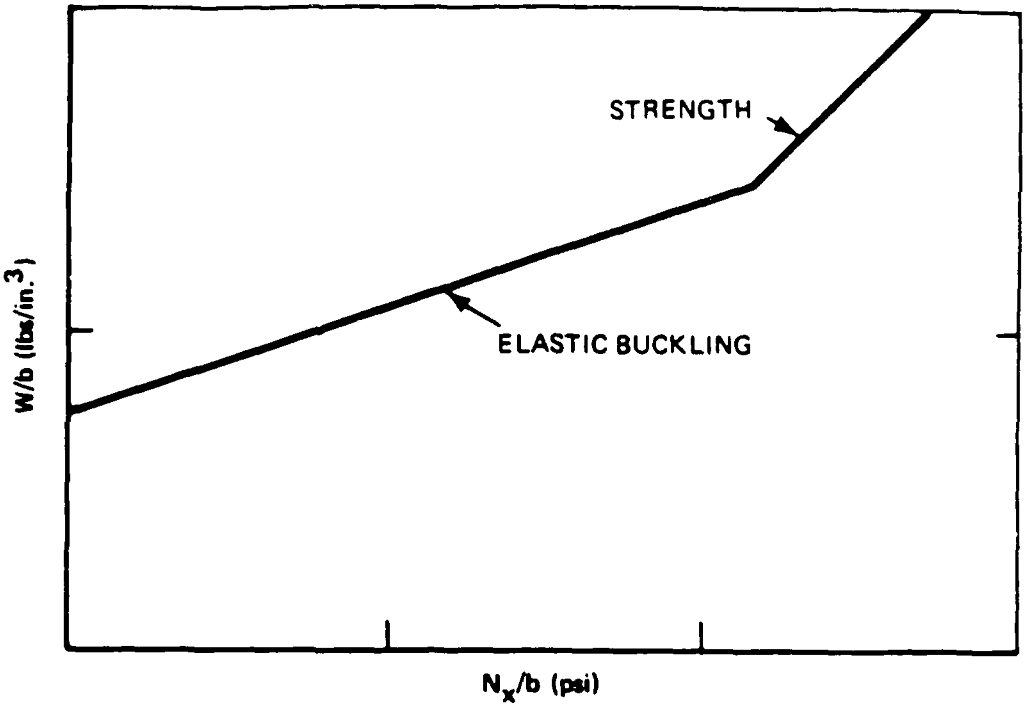

Figure 3. Plot for evaluating the efficiency of flat plates in axial compression.

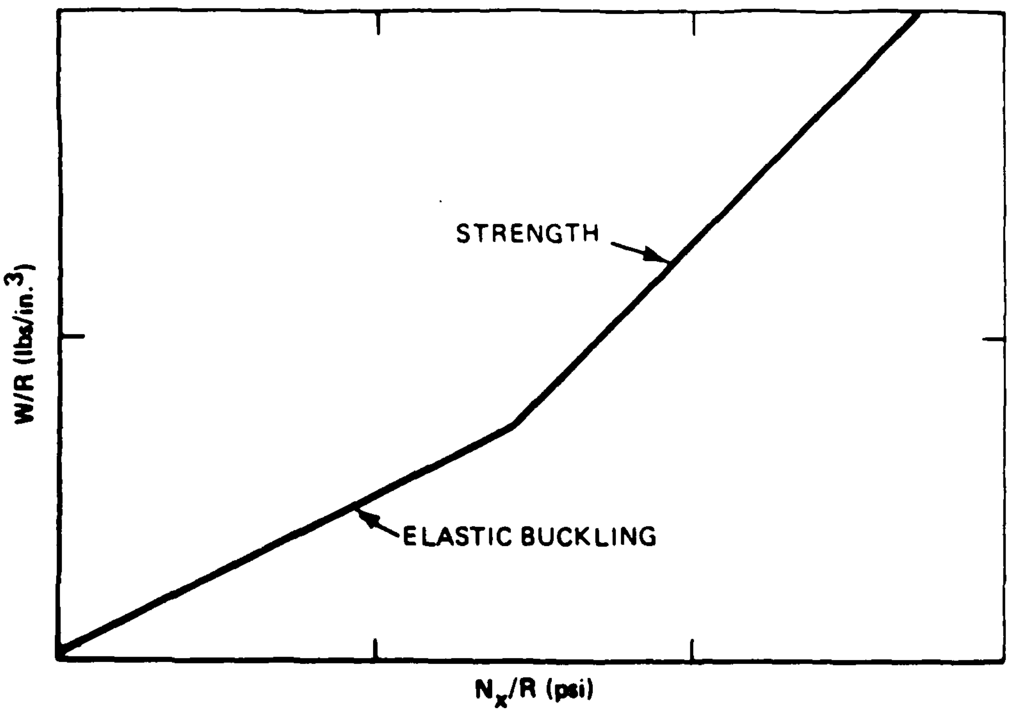

Figure 4. Plot for evaluating the efficiency of circular cylindrical shells in axial compression.

REFERENCES

1. Schoutens, J.E., "Metal Matrix Composite Materials Today," Invited Commentary, Journal of Metals, p. 43, June 1985.

2. Schoutens, J.E., and D.A. Zarate, "Structural Indices in Design Optimization with Metal Matrix Composite Materials," to be published in Composites.

3. Levitt, A.P., "Army Metal Matrix Composites Overview," Proceedings Sixth Metal Matrix Composites Technology Conference, 14-17 May 1985, Naval Postgraduate School, Monterey, CA, MMCIAC No. 000673, MMCIAC, Kaman Tempo, Santa Barbara, CA.

4. Schoutens, J.E., "The Elastic and Compressive Properties of Hybrid Metal Matrix Composites/Hexagonal Prismatic Cellular Solids," to be published in Composite Structures.

5. Schoutens, J.E., "Direct Measurements of Nonlinear Stress-Strain Curves and Elastic Properties of Metal Matrix Composite Sandwich Beams with Any Core Material," to be published in Journal of Materials Science.

6. Schoutens, J.E., Introduction to Metal Matrix Composite Materials, Third Printing, MMCIAC No. 000272, MMCIAC, Kaman Tempo, Santa Barbara, CA, June 1982.

7. Piggott, M.R., Load Bearing Fibre Composites, Pergamon Press, 1980.

8. Schapery, J., "Thermal Expansion Coefficients of Composite Materials Based on Energy Principles," J. Comp. Mater. 2, p. 380, 1968.

9. Kural, M.H., and B.K. Min, "The Effects of Matrix Plasticity on the Thermal Deformation of Continuous Fiber Graphite/Metal Composites," J. Comp. Mater. 18, p. 519, November 1984.

10. Dow, N.F., and E. Derby, Materials Science Corporation, Blue Bell, PA, personal communication, 1984.

11. Shanley, F.R., Weight-Strength Analysis of Aircraft Structures, First Edition, McGraw-Hill Book Company, 1952.

12. Hudson, C.C., and J.E. Schoutens, "Analysis of Dynamic Stresses and Motion of Pressure Gages in Alluvium," ISA Trans. 20, p. 13, 1982.

13. Gordon, J.E., Structures - Or Why Things Don't Fall Down, A Decapo Paperback, London, 1982.

14. Chamis, C.C., "Laminated and Reinforced Metals," Ed. Kirk-Othmer, Encyclopedia of Chemical Technology, Volume 13, Third Edition, John Wiley & Sons, p. 941, 1981.

15. Zweben, C., Metal Matrix Composites, Part 1, UCLA Extension Short Course Program, 11-15 June, 1984.